Damping of second sound in rotating He^4

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Experiments were performed in He^4 with second sound in an axial rotating resonator at $T = 1.52$ K in the presence of a constant transcritical heat flux ($> 10^{-3}$ W/cm^2). It is shown that second sound is additionally damped by the deformed vortex filaments. When the rotation is stopped, the damping is increased on account of the loss of regularity and of the random distribution of the vortices in the heat flux.

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It is known that in the presence of constant heat flux second sound is subject to an additional damping, on top of the usual one due to the viscosity and ther-

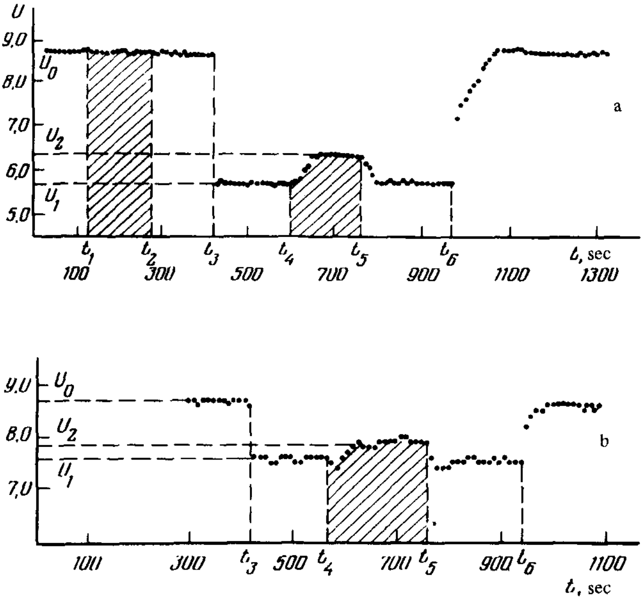

FIG. 1. Time variation of the resonant amplitude of second sound in an immobile and rotating resonator (shaded regions) upon application of an additional axial heat flux: a) 3.6×10^{-3} W/cm^2, b) 0.9×10^{-3} W/cm^2. The heat flux density from the radiator was 2×10^{-4} W/cm^2. Heat-flux density from thermometer 1.3×10^{-5} W/cm^2. Angular velocity $\omega = 1.05$ sec^{-1}.

mal conductivity of the normal component.[1–5] The additional damping is produced in threshold-like fashion, starting with a certain critical density of the heat flux ($\sim 10^{-3}$ W/cm^2).[2,3] At high densities, the excess damping increases linearly with increasing power.

Additional damping of the second sound is observed also in rotating helium. The experiments of Hall and Vinen[6] have shown that second sound propagating perpendicular to the rotation axis is additionally damping through scattering of the thermal excitations by the normal vortex cores. This damping is directly proportional to the angular velocity of the rotation, i.e., to the density of the vortex filaments. To the contrary, propagation of second sound along the rotation axis is not accompanied by additional damping. The excess damping of the second sound by the heat flux and by the vortex filaments, as shown by a comparison, is of the same order. If, in addition, it is also recognized that the dependence of the excess damping on the vortex-filament flux density is of the same character as the dependence on the heat flux, then the assumption that the additional damping is due to the same cause is inevitable.

To check on this assumption, we have observed the propagation of second sound in a rotating axial resonator in the presence of heat flow.

The resonator was a stainless-steel tube 90 mm long with inside diameter 15 mm. The radiator and receiver were, in the form of flat bifilar spirals,

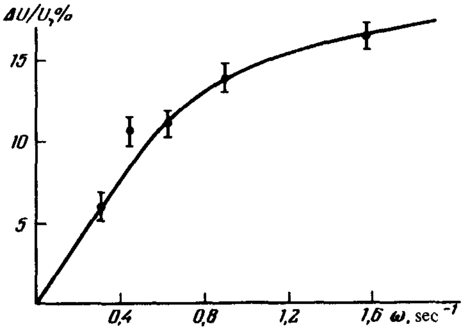

FIG. 2. Relative increase of the resonant amplitude of the second sound vs. the angular velocity at a heat flux 7 $\times 10^{-3}$ W/cm^2 from the radiator and 1.3 $\times 10^{-5}$ W/cm^2 from the thermometer.

were glued to the top and bottom of the resonator. The radiator was made of constantan wire of 50 μm diameter, and the receiver of phosphor-bronze wire of 40 μm diameter.

The helium flowed into the resonator through a capillary sealed into the top cover and in which a wire was snugly inserted to decrease the connection with the outside volume. The resonator Q was 200.

The second sound was excited and detected by the customary thermal procedure.[1-3] The measurements were made at a second-sound frequency 224 Hz at a temperature $T = 1.52$ K and at angular velocities up to 1.6 sec^{-1}.

The experiment was performed in the following manner (Figs. 1a and 1b): A power of 10^{-4} W/cm^2 was first applied to the radiator and receiver to effect the emission and reception of the second sound (Fig. 1a). At the instant of time t_1 the resonator was set to rotate at $\omega = 1$ sec^{-1}, in which case the second-sound amplitude remained unchanged. The rotation was stopped at the instant t_2. Next, at the instant t_3, a constant heat flux of 3.6×10^{-3} W/cm^2 was applied by the radiator. This decreased appreciably the amplitude of the second sound in the instrument. Rotation of the resonator, which was started at the instant t_4, lead to an increase of the amplitude of the second sound. When the rotation stopped (at the instant t_5) and the heat flux was turned on (at the instant t_6), the second-sound amplitude returned to its initial value. Figure 1b shows a plot of $U(t)$ for a heat-flux density 0.9×10^{-3} W/cm^2.

Attention is called to the following circumstance: When the power is turned on (t_3) the second-sound amplitude decreases relatively rapidly (< 10 sec), whereas when it is turned off a rather prolonged relaxation process is observed (~ 100 sec). The start and end of the rotation (t_4 and t_5) are accompanied by relaxation processes of approximately equal duration (~ 50 sec).

Analogous relations were observed by us also at other temperatures and at other frequencies. At low frequency, however, the effect manifests itself more strongly.

A study of the dependence of the effect on the applied power has shown that the second sound "feels" the rotation, starting with a heat flux density 10^{-3} W/cm^2 ($0.6-0.8 \times 10^{-4}$ W/cm^2), independently of whether this flux comes from the radiator or the receiver.

With increasing heat flux, the relative change of the second-sound amplitude $\Delta U/U$ (where $\Delta U = U_2 - U_1 U = U_1$, Fig. 1) increases. Thus, at $W = 10^{-2}$ W/cm^2 we have $\Delta U/U = 20\%$ if $\omega = 1.05 \times 10^{-1}$ sec^{-1}. However, the total damping in the immobile liquid also increases in this case $(U_0 - U_1)/U_0$ relative to the precritical regime.

Figure 2 shows the dependence of the relative increase of the second-sound amplitude on the angular velocity at a heat flux 7×10^{-3} W/cm^2.

Thus, in the presence of a transcritical heat flux in an axial resonator, the damping of the second sound increases both when the resonator is at rest and when it rotates, the damping in the mobile resonator being always larger than in the rotating one.

To explain the damping in the immobile liquid, we compare our data with the results of[3]. It is clear that in both cases we are dealing with the onset of a transcritical regime in the counterflow of the normal and superfluid components of helium II, such that vortices are produced in the resonator. The critical velocity obtained in[3] is

$$v_{sk} = \frac{\rho_n}{\rho_s} \frac{W_k}{\rho S T} = 5 \times 10^{-3} \text{ cm/sec} \qquad (d = 5.3 \text{ mm}, \quad T = 1.27\text{K}),$$

and in our experiments

$$v_{sk} = 3 \times 10^{-3} \text{ cm/sec} \qquad (d = 15 \text{ mm}, \quad T = 1.52\text{K})$$

where d is the resonator diameter. The results agree quite satisfactorily with the results of other experiments and the theoretical Feynman curve. We thus arrive at the conclusion that a hat flux $\gtrsim 10^{-3}$ W/cm^2 causes turbulization of the resting liquid helium II on account of the quantized vortices that are produced in it. The randomly oriented vortex filaments make the medium "turbid"[1)] and cause additional damping of the second sound.

Let us consider the damping of second sound in rotating helium. The rotation of the helium decreases the damping, because part of the turbulent vortices are dragged by the regular rotation. The medium becomes more transparent to axial second sound so that the additional damping decreases, but does not vanish completely.

We note that in homogeneously rotating helium, as shown in[7], the flux of sufficient magnitude can bend or even disrupt the regular vortex lattice. The instability is caused by the fact that any perturbation of the vortex filament in the presence of transcritical axial heat flux increases without limit. An estimate of the critical density of the heat flux, made in[6], yields a value 10^{-3} W/cm^2. For $T \sim 1$ K, the deformation of the filaments can reach 1 cm, in this case and this inevitably causes damping of the second sound.

Thus, the second-sound damping observed by us along the rotation axis in the presence of transcritical heat flux must be attributed to the bending and disruption of the vortex lattice. The experimental value of the critical velocity agrees well with the theoretical estimate of[6]. After the rotation is stopped, the vortex filaments do not vanish but, losing gradually their irregularity, they occupy arbitrary positions, causing the damping to increase.

In the subcritical regime the filaments are not deformed, they vanish completely after the rotation is stopped, and the damping of the second sound remains unchanged.

The results agree intrinsically with one another and with our ideas concerning the nature of the critical velocity. When the value v_{sk} is reached in the heat flux, the vortex filaments begins to grow in length intensively at the expense of the heat-flux energy. Evidence favoring this mechanism is provided by the fact that the critical velocities are equal in the resting and rotating liquid.

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[1] A term coined by É. L. Andronikashvili.

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